DURABILITY OF HIGH-VOLUME FLY ASH CONCRETE

A. Camões (1)

(1) Department of Civil Engineering, University of Minho, Portugal

Abstract

It is well known that the concrete industry has to contribute to the sustainability of construction. For this intent it is necessary to reduce the cement content without compromising the durability requirements of the concrete constructions. Therefore, large-scale cement replacement in concrete by by-products such as fly ash will be extremely beneficial from the overall ecological and environmental point of view.

In this context, an experimental research work was carried out focused on the evaluation of the possibility of producing low portland cement content concrete with enhanced or even high performances, including local by-products such as fly ash and common low cost aggregates without any previous treatment, i. e., as received. Three different concrete mixtures (incorporating large quantities of fly ash) were made and their mechanical, workability and durability properties were characterized. The total binder used (400 kg/m^3, 500 kg/m^3 and 600 kg/m^3) was composed by 40% of portland cement and 60% of fly ash by mass of the total cementitious material.

The overall results obtained show that the compressive strength requirements, in general, are fulfilled and that these concretes are highly durable. Thus, by using this type of concrete it is possible to build more durable structures and contribute as well to the construction sustainability.

1. INTRODUCTION

We are constantly faced with ever-larger ecological problems associated with the emissions of CO_2 into the atmosphere. It is well known that for every ton of portland cement produced, approximately one ton of CO_2 is released, which means that the portland cement industry contributes for about 7% of the total CO_2 emissions. Also, other adverse environmental impact of portland cement production refers to the high energy consumption. After aluminium and steel, the manufacturing of portland cement is the most energy-intensive process that consumes about 4 GJ of energy per ton [1]. So as to reduce the emission of CO_2 concerning the production of cement, we must reduce the use, and therefore the demand of portland cement.

However, the emission of CO_2 and the energy consumption are only some of the many problems we are facing nowadays. The inadequate durability of reinforced portland cement concrete structures and the increase of the volume of construction in the last few decades has resulted in a rampage of our natural resources. The availability of resources is finite and therefore we must alert the industry to the sustainability of construction.

The concrete industry, due to its large size, is the ideal home for economic and safe incorporation of millions of tonnes of industrial by-products such as fly ash. Therefore large-scale cement replacement in concrete by fly ash will be highly advantageous from the standpoint of cost, economy, energy efficiency, durability, and overall ecological and environmental benefits [1].

The worldwide production of coal ash is estimated to be more than 700 million tonnes per year of which at least 70% (500 million tonnes) is fly ash which is suitable to use as a pozzolan in concrete or other cement based products [2]. Unfortunately, only about 20% of the available fly ash is being used by the cement and concrete industry. To achieve a sustainable development of the concrete industry, the rate of the use of pozzolanic and cementitious by-products will have to be accelerated [1]. Incorporating high volumes of fly ash in concrete is one of the possible ways of making a green concrete.

For these reasons, an investigation has been carried out with focus on the possibility of producing low cost concrete with enhanced or even high performance, including local available materials such as fly ash (considered as low quality) and common aggregates without any previous treatment, i. e., as received.

Three different concrete mixtures incorporating a large amount of fly ash were made and some properties, such as mechanical, workability and durability were characterized. The total binder used (400 kg/m^3, 500 kg/m^3 and 600 kg/m^3) was composed by 40% of portland cement and 60% of fly ash by mass of the total cementitious material.

In order to study the mechanical properties, uniaxial compression and splitting tensile tests were made. Workability aspects were considered through the results of slump and flow tests of each mixture. The durability of these concretes was assessed by the permeability to oxygen and water, absorption of water into concrete under capillary and under immersion action, the non steady state chloride migration tests (CTH rapid method) and concrete electrical resistivity tests.

2. EXPERIMENTAL PROGRAMME

3.1 Materials, mix design, manufacture and curing

In the current experimental program, three different concrete mixtures were produced using CEM I 42.5 R portland cement (C), fly ash (FA), natural river sand (maximum aggregate size of 2.38 mm and fineness modulus of 2.53), crushed granite coarse aggregate (maximum aggregate size of 9.53 mm and fineness modulus of 5.75), and superplasticizer (SP).

The fly ash used was produced from the Pego Power Plant located in Portugal, with an average loss on ignition (LOI) which varied between about 6% and 9%. These high LOI values belong to the upper class (category C) established by European standards (EN 450:2005) or may exceed the proposed limit. However, studies have shown that, at least for this fly ash, the high LOI is not impeditive of its use on cement pastes, mortars and concretes [3,4]. Table 1 shows the oxide content of the cement and the fly ash used. Table 2 presents the estimated compound composition of the cement using Bogue's expressions [5]. Table 3 shows some physical characteristics of the cement and the fly ash.

Table 1: Oxide composition of the cement and fly ash

Chemical composition	Cement (%)	Fly ash (%)
SiO_2	19.74	60.87
Al_2O_3	4.13	20.40
Fe_2O_3	3.27	7.82
CaO	62.99	2.72
MgO	1.90	1.40
SO_3	3.02	0.22
Cl^-	0.04	0.00
Free Lime	1.43	0.00
Loss on ignition	3.2	7.30
Insoluble residue	0.90	–

Table 2: Estimated compound composition of the cement

Compound composition	(%)
C_3S	66.33
C_2S	4.06
C_3A	5.42
C_4AF	9.94
$C\underline{S}$	5.13

Table 3: Physical characteristics of the cement and the fly ash

Physical characteristics	Cement	Fly ash
Specific Weight (kg/m^3)	3120	2360
Blaine Specific Surface (m^2/kg)	382.5	387.9
Fineness – 45 μm (%)	2.9	27.3
Water demand (%)	28.7	29.7

The superplasticizer (SP) was a last generation copolymer based, with a solid content of 20%. In previous work [6], the optimum superplasticizer solid content was estimated to be between 0.5% and 1.0% by mass of the binder. The value of 1.0% was adopted in this research work.

The proportions of the concrete constituents are presented in Table 4 as well as the workability obtained using the slump and the flow table tests.

Table 4: Concrete mix designs and workability

Mix	W/B	C (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Slump (mm)	Flow (mm)
C400	0.27	160	240	780	1170	185	480
C500	0.23	200	300	731	1097	175	470
C600	0.20	240	360	685	1027	195	510

The water binder ratio (W/B) was determined experimentally by trial batches in order to obtain a similar slump of about 185 mm for all the compositions.

Cubic specimens with 100 mm edge and cylindrical specimens of 150 mm diameter and 300 mm height were moulded in order to evaluate, respectively, the compressive strength and the splitting-tensile strength of the concrete mixes studied. For each composition a concrete plate was also cast, to obtain cored specimens for some durability tests.

Before demoulding, the specimens were cured at 21 ºC and at a constant relative humidity of 80%. The specimens were removed from the forms 48 hours after casting and were stored immersed in lime saturated water at 21 ºC until testing.

3.2 Testing procedures

The compressive strength test, performed in cubic specimens of 100 mm edge according to EN 12390-3:2002, was used as a reference test procedure. The splitting-tensile strength test was carried out based on EN 12390-6:2000 in cylindrical specimens of 150 mm diameter and 300 mm high. These mechanical tests were performed on 3 specimens at 7 and 28 days and on 6 specimens at 365 days of age.

The capillary water absorption test followed the LNEC E393:1993 specification, which is based on the RILEM CPC11.2 draft recommendation. For each composition 4 cubic specimens with 100 mm edge were tested.

The water absorption by immersion in vacuum was also performed (LNEC E395:1993) on 5 different cylindrical cored specimens of 45 mm diameter and 40 mm thickness.

The permeability to oxygen and water tests was performed using the apparatus developed at Leeds University [7]. This device (Fig. 1) ensures that the specimen is subjected to a steady state flow of the fluid that passes through the sample under a given pressure during a certain period of time. The same specimens used in the water absorption test by immersion were afterwards subjected to oxygen permeability and then to water permeability test.

Figure 1: Oxygen and water permeability tests

In order to test the resistance against chloride penetration, an accelerated non-steady state migration test method was applied according to NT Build 492:1999 (Fig. 2). The electrical resistivity of the specimens at the beginning of the test was also measured. Four cylindrical specimens of 75 mm diameter and 50 mm thickness were tested.

Figure 2: Rapid chloride migration test (NT Build 492:1999)

4. EXPERIMENTAL RESULTS AND DISCUSSION

Table 5 includes the main results obtained in the laboratory experimental program. Each value is the average of the results measured, followed, after dash, by the corresponding coefficient of variation (%).

Table 5: Experimental results obtained

	Age (days)	C400	C500	C600
Compressive strength, f_{cm} (MPa)	7	21.3/2.1	26.9/2.2	36.8/2.5
	28	33.9/5.4	47.0/0.1	52.8/2.0
	365	41.0/5.2	58.3/4.4	79.1/2.2
Splitting-tensile strength, $f_{ctm,sp}$ (MPa)	7	1.6/4.9	2.0/24.1	2.0/7.9
	28	1.8/14.7	2.0/8.9	2.8/2.8
	365	3.9/18.3	4.2/9.7	4.2/15.3
Capillary absorption, S_c (kg/m^2/min$^{0.5}$)	365	0.046/9.7	0.047/11.8	0.046/6.3
Porosity, P (%)	365	11.9/2.5	10.8/3.1	11.8/3.5
Oxygen permeability, K_O (x10^{-17} m^2)	365	3.9/47.6	0.9/26.3	0.1/24.2
Water permeability, K_W (x10^{-18} m^2)	365	2.16/112.2	0.39/51.0	0.35/77.8
Rapid migration test, D (x10^{-12} m^2/s)	365	0.96/21.0	0.60/26.9	0.53/54.6
Electrical resistivity, ρ (Ωm)	365	1094.2/58.0	1416.8/62.9	1522.6/37.2

4.1 Compressive and splitting-tensile strength

Fig. 3 shows the mechanical strength time development of the tested concretes. From Table 5 and Fig. 3 it can be seen that it is possible to produce a moderate-strength concrete containing only 160 kg/m^3 of portland cement content while achieving a 28 days compressive strength of about 35 MPa. This compressive strength is typical for conventional concrete which correspond to the majority of the construction requirements. However, this kind of concrete may be also used when higher strength is necessary. Increasing the cement content to 200 kg/m^3 or 240 kg/m^3 the 28 days compressive strength goes up to about 45 MPa or 55 MPa.

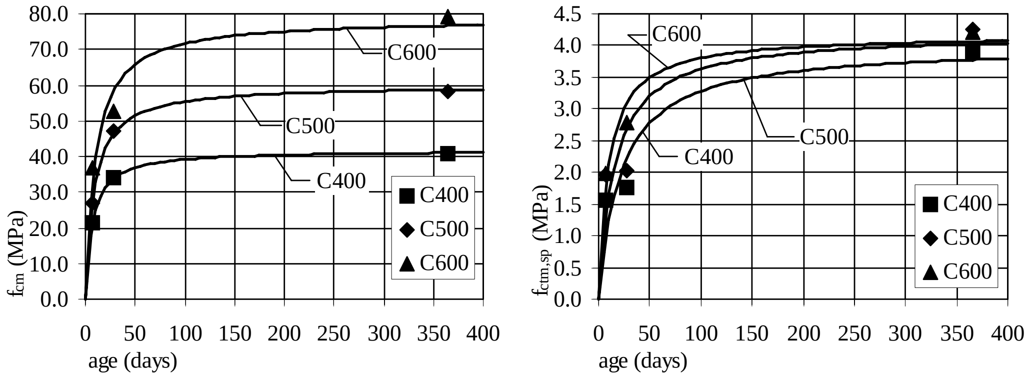

Figure 3: Time development of average compressive strength (f_{cm}) and average splitting-tensile strength ($f_{ctm,sp}$)

The splitting-tensile strengths obtained are comparable to those obtained in plain cement conventional concrete (using ordinary portland cement or CEM I 42.5 cement) with similar compressive strengths.

It is important to notice that these concretes can achieve adequate 28 days compressive strengths and their mechanical strengths keep on increasing considerably with age (more than CEM I cement concretes) because of the pozzolanic reaction of fly ash. At one year of age the studied concretes reached about 40 MPa, 60 MPa and 80 MPa of compressive strength.

4.2 Capillary absorption and porosity

The results presented in Table 5 and Fig. 4 express the coefficient of capillarity absorption, S_c, which correspond to the slope of the curves representing water absorbed per unit area versus square root of time during the initial 4 hours of testing.

This test can not distinguish between concretes with different binder content and the values obtained show a rather low capillary absorption, indicating that these concretes may be classified as high durability ones.

Like the capillary absorption test the water absorption by immersion in vacuum (porosity) was not sensitive to the different concretes studied. The porosity values obtained can be considered higher than expected for high durability concretes. This may be due to the high carbon content of the fly ash particles that possibly absorbs great amounts of water.

4.3 Oxygen and water permeability

For the oxygen and water permeability, the increasing of the binder content improves the concrete performance. This aspect seems to be more relevant when comparing C400 with the other mixtures. For the water permeability it seems that there is no advantage in increasing the overall content of binder from 500 kg/m^3 to 600 kg/m^3. The values are in accordance to general experience for low permeability concrete and the order of magnitude between the values of water and oxygen permeability observed for concrete tested with the Leeds permeator is also in accordance with general experience [8]. The low coefficients of permeability obtained indicate that the tested concretes showed high durability.

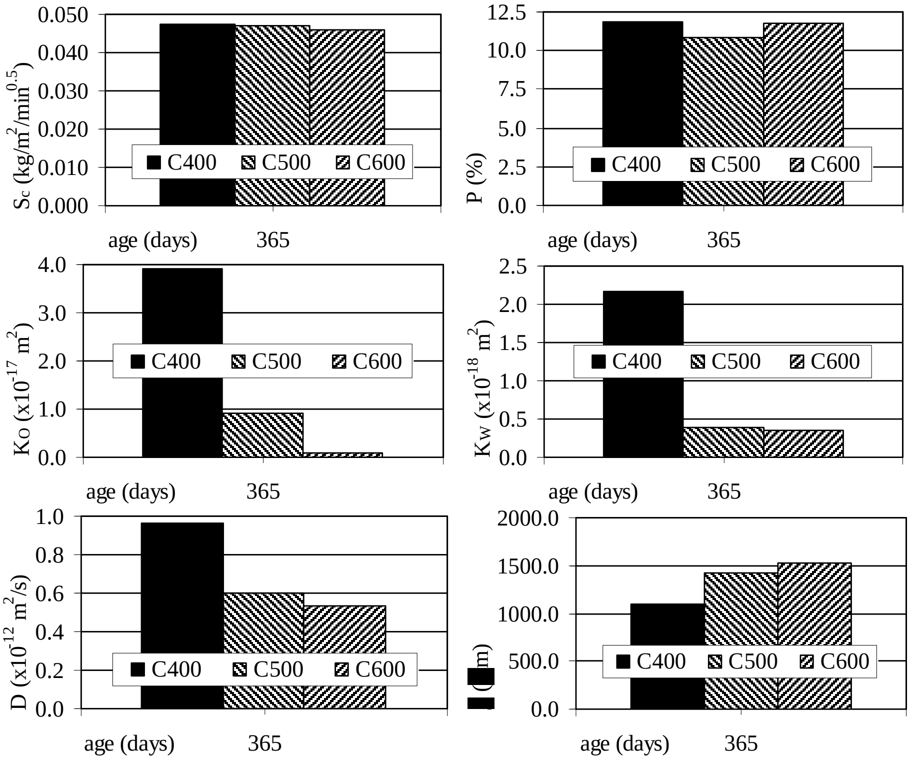

Figure 4: Durability test results

4.4 Chloride migration

As shown in Table 5 and Fig. 4, the coefficient of diffusion improves in performance as the binder content increases. This effect is more pronounced from C400 to C500 than from C500 to C600. Based on previous experience [9], the obtained results indicate that all the concretes produced have an extremely high resistance against chloride penetration.

4.5 Electrical resistivity

The electrical resistivity was determined using the initial current intensity values of the chloride migration test. Ohm's Law was used to estimate the resistivity values. Table 5 and Fig. 4 indicate that the overall results obtained are in accordance with the apparent coefficient of diffusion measured. The results show that, for the studied concretes, there is a close relationship between chloride diffusivity and electrical resistivity and that the difference of the various binders to resist chloride penetration into concrete can be detected by this test.

5. CONCLUSIONS

Based on the obtained results on the high-volume fly ash concretes tested the following conclusions can be stated:

- The compressive strength tests indicate that concrete with about 35 MPa strength at 28 days can be produced using 160 kg/m^3 of cement and 400 kg/m^3 of binder content which is sufficient for the majority of the structural concrete constructions' applications.

- This kind of concrete can also be used when higher strength is needed. Increasing the binder content to 500 kg/m^3 or 600 kg/m^3, and maintaining the 60% of cement replaced by fly ash, the 28 days compressive strength increases respectively to about 45 MPa or 55 MPa.
- Comparing these concretes to plain cement ones, they have the advantages of the long term strength gains. Results show that for one year old the compressive strengths reach about 40 MPa (C400), 60 MPa (C500) and 80 MPa (C600).
- All the determined durability parameters show that these concretes seem to be highly durable ones, which permit to classify them as high-performance concretes.

Thus, these high volume fly ash concretes, made with high workability and with a high carbon content fly ash provides significant advantages over conventional plain portland cement concrete. For the widespread usage of these concretes, it is important to note that the compressive strength requirements, in general, are fulfilled and that with these concretes it is possible to build more durable structures while contributing to the construction sustainability.

However, it is important to notice that these concretes were not tested for all types of corrosive actions, namely to frost attack. Concerning this kind of attack, it can be expected that, due to the high carbon content of the fly ash, these concretes could not be considered as high durable ones.

It is also relevant to consider that the field curing conditions can significantly differ from the tested ones, and the overall quality of these high-volume fly ash concretes can be drastically affected if proper curing were not assured.

REFERENCES

[1] Malhotra, V.M. and Mehta, P.K., 'High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories', CANMET (Ottawa, Canada, 2002).

[2] Mehta, P.K., 'Concrete Technology for Suitable Development', *Concrete International* **21** (11) (Nov. 1999) 47-53.

[3] Camões, A., Aguiar, B., Jalali, S., 'Durability of Low Cost High Performance Fly Ash Concrete', Proceedings of IAUS 2003, International Ash Utilization Symposium (Lexington, Kentucky, USA, 2003), in CD-Rom.

[4] Camões, A., Ferreira, R.M., Aguiar, J.L.B., Jalali, S., 'Durability of High Performance Concrete With Fly Ash', Concrete for Extreme Conditions, Proceedings of the International Conference Challenges of Concrete Construction (Dundee, Scotland, U.K., 2002) 357-366.

[5] Bogue, R.H., 'Chemistry of Portland Cement', Reinhold (New York, USA, 1955).

[6] Camões, A., 'Influence of Mineral Admixtures in the Fresh Behaviour of Superplasticized Concrete Mixes', Proceedings of INCOS’05, International Conference on Concrete for Structures, (University of Coimbra, Portugal, 2005) 1-8.

[7] Cabrera, J.G., 'Design and Production of High Performance Concrete', Proceedings of International Conference, Infrastructure Regeneration and Rehabilitation Improving the Quality of Life Through Better Construction, (Sheffield, U.K., 1999) 1-14.

[8] Ferreira, R.M., 'Evaluation of Concrete Durability Tests', Masters Thesis, School of Engineering, University of Minho, (Guimarães, Portugal, 2000).

[9] Gjørv, O.E. 1996. 'Performance and Serviceability of Concrete Structures in the Marine Environment', Proceedings of Symposium on Concrete for Marine Structures, ed. by P.K. Mehta, CAN-MET/ACI (1996) 259-279.